SIGNAL PROCESSING AND CHARACTERIZATION OF THE AUDIO EVOKED CORTICAL RESPONSE

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THESIS

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OF THE
AUDIO EVOKED CORTICAL RESPONSE

by

Russell Eugene McWey

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Thesis Advisor: G. Marmont

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Block #20 continued

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Signal Processing and Characterization of the Audio Evoked Cortical Response

by

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The audio evoked cortical response to stimuli consisting of audio "clicks" of varied frequency was analyzed. Analysis of the encephalogram was accomplished through the use of a computer based signal processor which used signal averaging as the primary processing mode to produce a signal for analysis. A "unit response" wave form was identified and its relationship to the composite response to multiple stimuli was investigated. Using the unit response as a criterion with multiple audio click stimuli, concepts of initial reaction time and integrative processing were identified.

TABLE OF CONTENTS

LIST OF FIGURES

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I. INTRODUCTION

The brain and its functioning have only recently been investigated to any detail with adequate sophistication. It is certainly no understatement to say research in this area is in its infancy. Only through recent advancements in electronic and computer technology have new pathways to cortical processing been opened.

By analysis of the cortical electrical signal, the electroencephalogram, insights into the brain's functioning are now available. Latest developments in the area of visual evoked cortical responses have allowed eye fault diagnosis while avoiding the patient's subjectivity that is present in standard eye testing methods. This development can and is facilitating eye fault diagnosis in children who are too young to speak or identify symbols on an eye chart.

It is the intent that the research involved in this thesis research will lead to the development of a similar audio fault diagnosis. This will also be accomplished through signal processing of audio evoked cortical responses.

II. BACKGROUND

Electroencephalogram production has been discussed in many research papers and neuroscience textbooks. But analysis of the electroencephalogram has not been productive until computer technology had developed sufficiently to allow adequate signal processing. It is not the intent of this thesis to discuss basic electroencephalogram production, but rather to analyze the produced EEGs for their possible meaning and characterization.

It is then sufficient to say that electric potentials in the brain can be observed by differentially amplifying the signal between two electrodes placed on the head. A unipolar measurement can be made using one electrode attached to the earlobe and another electrode positioned somewhere on the scalp. For audio evoked potentials, the vertex of the skull was found to be the area of electrode placement for the optimum cortical signal.

A final comment is to point out that the EEG is a summative signal created by the firing of many neurons within the brain and brain stem. Positioning of the electrodes can localize primary areas of processing. Brain processing maps have been determined in this manner. The important point, however, is that the EEG is a composite signal constructed of many smaller neuron signals firing in a specific manner. The neuron firings represent processing of many signals in many areas within the brain.

III. PHYSIOLOGICAL BACKGROUND

Possible analysis of the audio evoked response requires understanding of the audio sensing organs of the body and conductive paths from the audio centers to and within the brain.

The very basic and first stage of audio sensing occurs in the ear. The ear can be subdivided into three parts; the outer ear, the middle ear, and the inner ear. (See Figure 1.)

The outer ear consists of the pinna and the external auditory canal. The pinna serves as a sound collecting device and the canal serves as a conduction tube for sound waves to the tympanic membrane which lies at the innermost end of the external auditory canal.

The middle ear is composed of the tympanic membrane and the ossicular chain. The ossicular chain is composed of three small bones; the malleus, incus, and stapes. These bones serve as a conduction path for sound vibrating the tympanic membrance. Sound waves cause the tympanic membrane to vibrate which in turn cause the ossicular chain to vibrate which eventually cause the oval window of the inner ear to vibrate. Specifically, the tympanic membrane is attached to the malleus. The malleus then attaches to the incus which attaches to the stapes which finally attaches to the oval window. The three bones act as a lever system which amplifies

the audio signal mechanically. Together with the surface area of the tympanic membrane, the ossicular chain provides a force multiplication of about 17. This multiplication is variable and can be controlled by the stapedius muscle which can effectively reduce the leverage and does so when high volume sounds are encountered. The middle ear has another function besides simple amplification. It acts as a transducer. The inner ear serves as a coupling between the sound waves in the air and the sound waves in the middle ear which travel in a liquid medium. Thus there is an impedance matching function between the air and the liquid medium in the inner ear that is performed by the middle ear.

The inner ear is located within the temporal bone and is composed of three major parts. The oval window is the first conduction path in the inner ear. It is the interface between the middle ear and the cochlea. The round window is also an interface between the middle ear and the cochlea but serves only as a pressure relief for the vibrating fluid within the cochlear canal. The cochlea is attached to three semicircular canals which also contain fluid. These canals are the primary sensor for the vestibular system but play no role in audio sensing.

The cochlea is a spiraled tube which, when cross sectioned, is composed of three canals. (See Figure 2.) The canals are the vestibular canal, the tympanic canal, and the cochlear canal. The tympanic canal is bounded at one end by the oval window and the vestibular canal is bounded at one end by the

round window. The tympanic and vestibular canal join together at the apical end of the cochlea. Reissner's membrane, which is thin and flexible, forms the partition between the vestibular and cochlear canals and the basilar membrane, which is quite rigid, forms the partition between the cochlear and tympanic canals. Thus sound energy causes vibration of the oval window induces fluid motion in the liquid within the vestibular and tympanic canals and in turn excites the cochlear canal. Motion in the cochlear canal then stimulates sensory receptors which produce a neural signal.

The organ of Corti lies on the basilar membrane. It is the sensory reception organ within the cochlea. It is composed of 20,000 hair cells with each row containing four or five cells. There are three outer hair cells and one inner hair cells per row. The hairs protrude through the reticular lamina to the tectorial membrane. The tectorial membrane is a fibrous material which shears back and forth over the hair cells. Motion of the basilar membrane causes the shearing action which causes the hairs of the hair cells to move and excite the sensory cells associated with those hair cells. The action potentials elicited from the sensory cells then travel along the audio portion of the VIII th cranial nerve.

The cochlea itself acts as an attenuation device which damps out higher frequencies as the distance along the canals from the oval window increases. Thus high frequencies will tend to excite the hair cells closest to the oval window and

low frequencies will tend to excite the hair cells further away from the oval window. Thus the cochlea provides frequency discrimination through position of stimulation along the canals of the cochlea. In addition, it is known that the brain can cause selective inhibition of the hair fibers about a point along the canals of the cochlea. This can thus allow very fine frequency discrimination.

There are three known types of potentials which are transmitted from the cochlea along the VIII th nerve. The first is the cochlear microphonic potential. It is an analog signal with respect to the audio signal. There is no threshold value and no significant latency involved with this potential. The potential appears to originate from the outer hair cells. The second potential is called the negative summation potential. This potential represents the RMS value of the audio signal. This potential is associated with the inner hair cells and is related to the change in endolymph-perilymph potential within the cochlear canals. Large amplitudes can result in a change of potential from 80 to 70 millivolts. The third potential is an action potential. The action potential is an all-or-nothing type response which can occur up to the maximum rate of 1000 times per second per axon. The action potential is the means by which coded nerve impulses pass to the audio processing portions of the brain.

An audio pathway exists through the central brain to the transverse temporal gyrus of the cortex. Along this pathway

there are many nerve synapses, intersections and terminations. Each part of the audio pathway plays some role in the processing of an audio signal to a meaningful code which is recognizable to the brain. Processing is conducted at all levels of the brain from the cochlear nuclei up through the medial geniculate nuclei to the transverse temporal gyrus where speech recognition and identification finally occurs.

The audio pathway is far from simple and localization of one type of sub-processing has yet to be accomplished. By placing an electrode at the vertex of the skull one can get a composite EEG of the neuron firings along the entire audio pathway. It is from the composite that individual identification of local processing may be accomplished. Present auditory EEG analysis is beginning to identify these local processing points and relate their function to the entire process which allows decoding of nerve impulses to meaningful symbols.

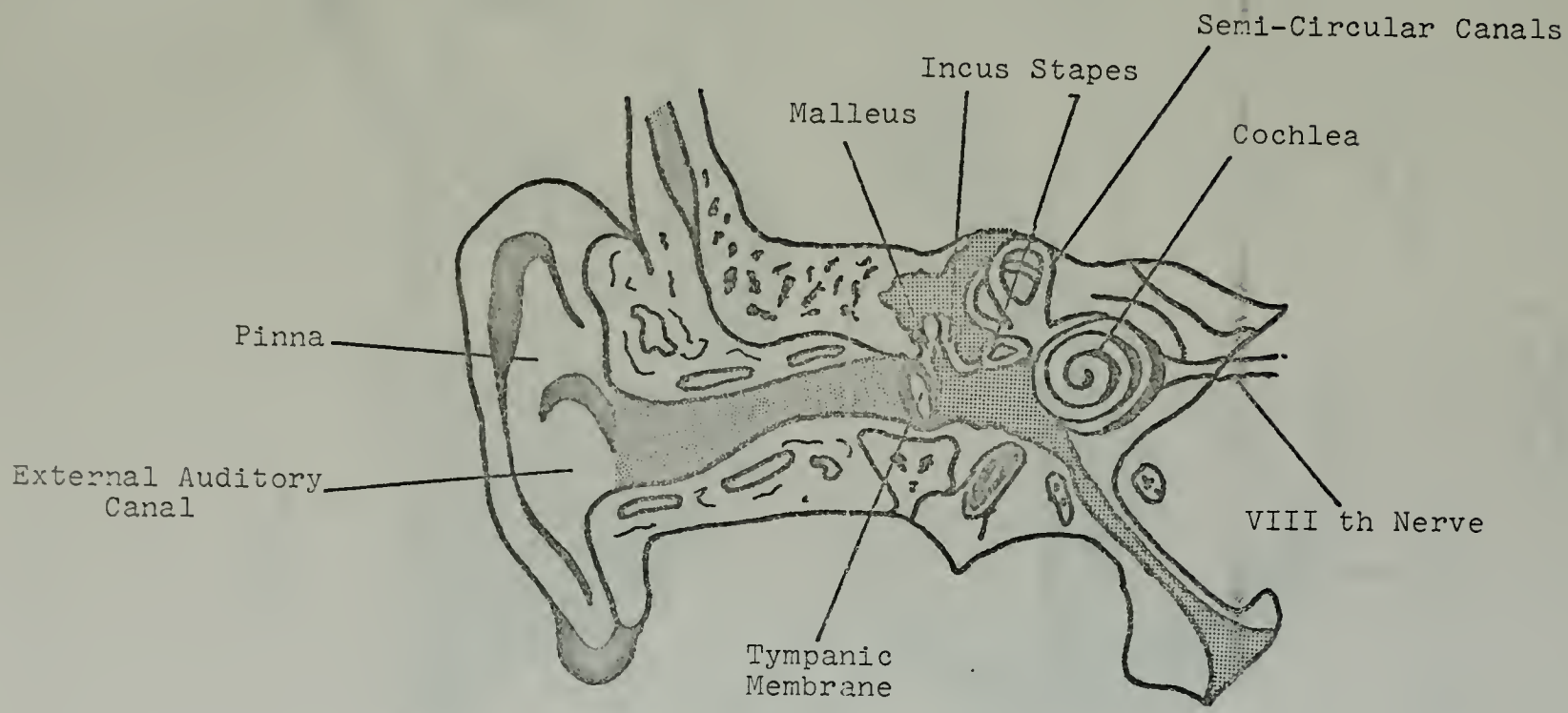


Figure 1. Physiology of the Ear.

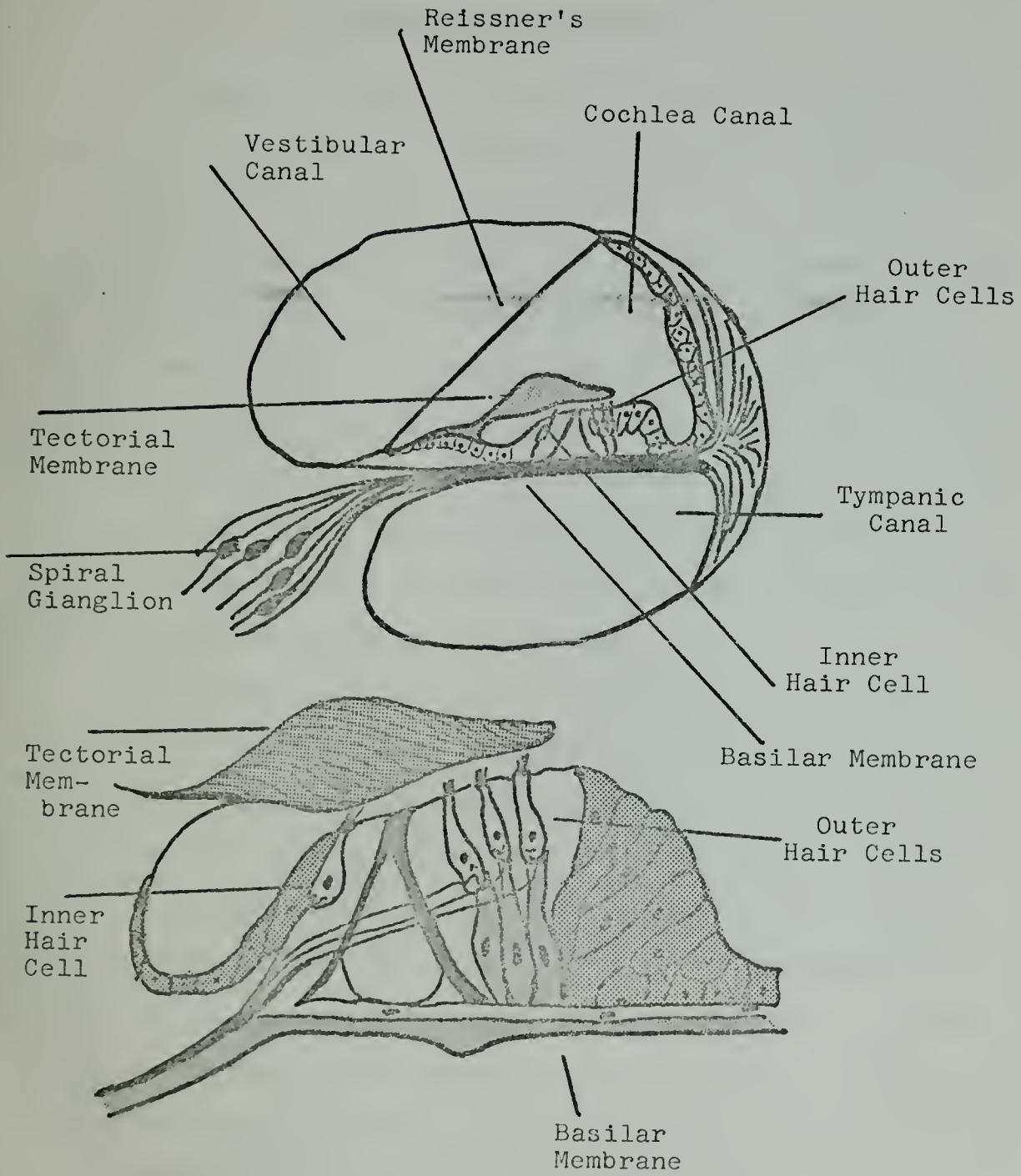


Figure 2. Cochlear Cross-Section and Organ of Corti.

IV. NEUROLOGICAL BACKGROUND

The auditory portion of the VIII th nerve is made of the axons of bipolar cells. (See Figures 3 and 4.) The dendrites of these cells are then distributed to the organ of Corti. The nerve impulses created when the basilar membrane vibrates and stimulates the sensory cells in the organ of Corti are transferred to the dendrites of the bipolar cells. The axons then pass outward through the spiral lamina and join to form the auditory portion of the VIII th cranial nerve. The nerve then traverses the internal auditory canal and terminates in the dorsal and ventral cochlear nuclei which is situated near the junction of the medulla and pons.

The cochlear nuclei, which are attached to the surface of the inferior cerebellar peduncle, contain cell bodies in the auditory pathway. The axons of these cells enter the tegmentum of the pons. From this point the axons intersect and form the trapezoid body or they end in the superior olivary nucleus. As the axons travel to the trapezoid body they form the dorsal and ventral striae. The dorsal striae originate in the dorsal cochlear nucleus and pass behind the inferior cerebellar peduncle and the ventral striae originate in the dorsal and ventral nuclei and pass ventral to the inferior cerebellar peduncle.

The nerve fibers that proceed from the trapezoid body continue to the lateral lemniscus. The lateral lemniscus

then terminates in the auditory nucleus of the inferior colliculus. The nerve fibers then pass diagonally and anteriorly across the side of the mesencephalon and terminate in the medial geniculate body. The medial geniculate nuclei is situated behind the basis pedunculi at about the level of the superior colliculi. Axons from the cell bodies within the medial geniculate nucleus then travel through the sublentiform portion of the internal capsule and terminate in the auditory area of the cerebral cortex. The auditory area of the cerebral cortex is along the anterior transverse temporal gyrus which is a fissure in the cerebrum that runs diagonally upward from the lower anterior temporal region of the skull to the point of intersection of the temporal, parietal, and occipital regions of the skull.

The apparent auditory pathway to the cortex consists of a chain of nerve fibers consisting of at least four neuron links. The first cell has its body in the spiral ganglion, the second in one of the cochlear nuclei, the third in the inferior collicular nucleus, and the fourth in the medial geniculate body.

The actual tracing of the auditory pathway is still further complicated by terminations and relay areas along the pathway previously discussed. Secondary auditory fibers from the cochlear nuclei end in the olivary nuclei of both the same side and the contralateral side. Still other fibers terminate in or send collateral information to the nucleus of the lateral lemniscus. The fibers form these nuclei travel

through the lateral lemniscus and usually terminate in the inferior colliculs. Still further complications arise when it is noted that fibers from the superior olivary nucleus may enter the lateral lemniscus of the same side or they may intersect in the trapezoid body and enter from the opposite side.

As can be seen, there are numerous pathways in which auditory impulses that occur in either ear may propagate to the auditory areas of both cerebral hemispheres. Various pathways include the bilateral termination of cochlear axons in the cochlear nuclei and in the superior olivary nucleus. It may also include the intersection of some fibers in the lateral lemniscus at the level of the inferior colliculi.

Bilateral neural processing of audio signals has been verified. Unilateral removal of the lateral lemniscus, medial geniculate body, or auditory area cortex may occur with only minor unilateral impairment which subjectively appears bilateral.

An apparent point concerning location of the processing path is that it is located in the brain stem and central portions of the brain. As previously noted, processing of the audio signal occurs along the entire audio pathway. The decoding of a certain sound begins immediately within the cochlea and is further decoded along the pathway. Upon arriving at the transverse temporal gyrus, the signal is sufficiently processed to allow pitch, amplitude, and locality identification. Still further, the signal is so decoded as

to allow for combinations of sounds to be recognizable as parts of speech. It can be seen then that understanding of audio processing is only one small step in the understanding of total brain functioning. This understanding can thus be extended to produce useful methods of bio-feedback to aid in efficiency in performing mental tasks of many kinds.

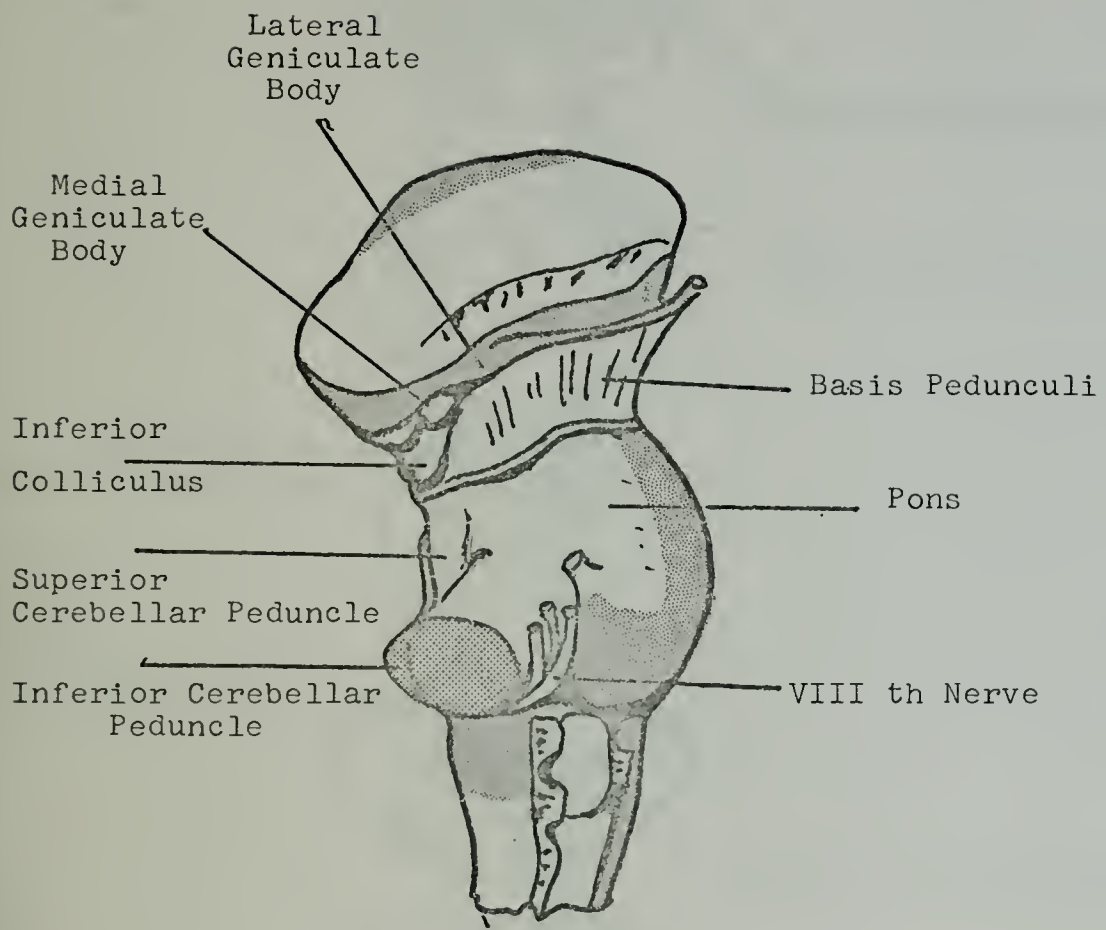


Figure 3. Physiology of the Brain Stem.

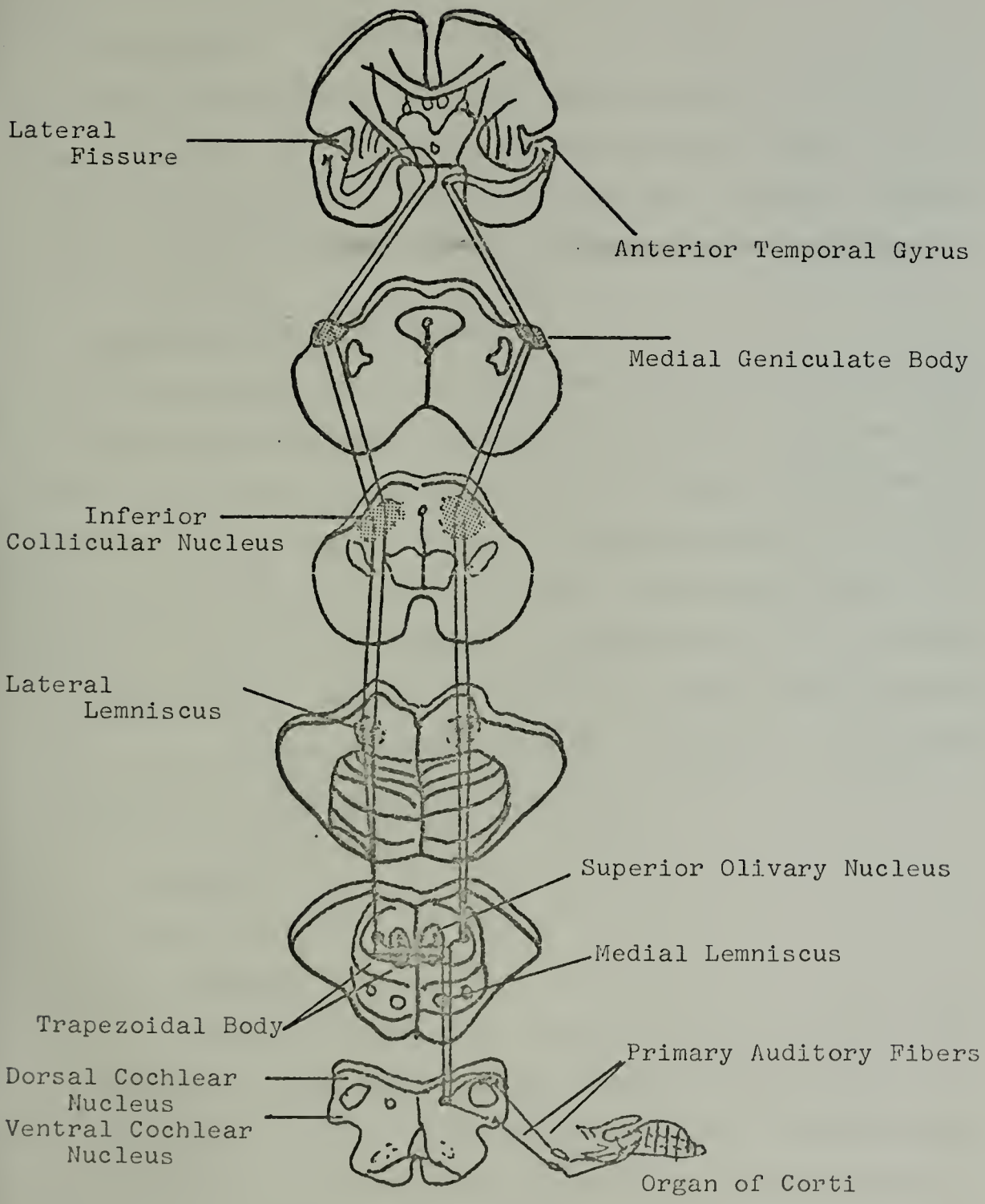


Figure 4. The Auditory Pathway.

V. METHOD

A. SUBJECTS

The subjects used for audio testing were, for the most part, members of the Bio-Engineering research team. All subjects were between the ages of 11 and 54. A total of twelve subjects were tested. Two were females and ten were males.

B. EXPERIMENTAL ENVIRONMENT

The testing area consists of two rooms. One of the rooms is an isolation screen room where the subject remained alone while being tested. The screen room provides sufficient isolation for the subject while providing sufficient electrical isolation from surrounding 60 Hertz signals and other electrical noise which might cause contamination of the electroencephalogram. The second room contains the signal processor and other related testing equipment. Control of all testing equipment is conducted from this room

C. EQUIPMENT

(See Figure 5.)

1. Trigger

This was produced by a variable width, variable frequency pulse generator. The trigger pulse used was a .5 second pulse width at 1 Hertz. The trigger simultaneously activated the signal processor and acted as a .5 second gating pulse for the signal generator.

2. Signal Generator

The signal generator was operated in a gated mode so that its output would be rectangular pulses or sine waves at a specific frequency which were gared on for .5 seconds of every one second period.

3. Differentiator

The differentiator was a simple R-C circuit which was used to transform the rectangular pulses to sharp spikes. The spikes were then passed to the audio amplifier which reproduced the spikes as audio clicks. Spikes were desired as they provide a sufficiently uniform distribution in the frequency domain; a condition necessary to insure sufficient stimulation over most of the audio frequency spectrum to stimulate most of the audio neurons from the cochlea to the audio processing centers of the brain.

4. Audio Amplifier

A Dynaco 80 watt audio amplifier was used to amplify the spikes produced by the differentiator. The amplified signal was then passed to the headphones and presented to the subject. The amplifier had a flat response over the audio frequency range.

5. Headphones

High quality dynamic and electro-static earphones were used for the audio testing.

6. Speakers

High quality, flat frequency response monitor speakers were used as a second type of audio source.

7. EEG Amplifier

The EEG signals from the electrodes were passed to the EEG amplifier. The amplifier had a gain of 4000.

8. Filter

The amplified EEG signal was then passed to an active filter which removed all signals above 100 Hertz. The filter had a gain of approximately 2.5. The filter gain together with the EEG amplifier gain combined give a total EEG signal gain of about 10^4.

9. Electrodes

Four Beckman EEG electrodes were used. The primary electrode was attached to the vertex of the head. The vertex was found to be the position which produced the optimum cortical response. The second electrode was placed at the junction of the occipital, parietal, and temporal portions of the head. The third electrode was attached to the earlobe and served as reference level for the other two head electrodes. A fourth electrode served as system ground. This electrode was attached to the skin over the collar bone and served to block electrocardiogram signals from contaminating the electroencephalogram signals. The two head electrodes were positioned by use of a specially designed electrode helmet. The two remaining electrodes were positioned using conductive electrode paste and special adhesive discs.

10. Electrode Helmet

A new design in electrode positioning apparatus was used to aid in making reliable, rapid, and uniform electroencephalogram measurements. Two major problems exist in EEG measurements. The first problem concerns electrode placement. Present techniques involve adhesive attachment of electrodes. This leads to electrodes which are not stationary with respect to the skin. Drying of the adhesive or stretching of the adhesive material allows electrode movement. Electrode movement causes a change in the resistance between the electrode and the skin. This obviously leads to varying voltage measurement which can provide inconsistent EEG measurements. The second problem that exists involves the conductive electrode paste. Drying electrode paste can also cause a resistance change between the electrode and the skin. In addition, perspiration can also mix with the paste which again causes a resistance change and inconsistent EEG measurements. These two problems were resolved through the design of a special electrode helmet. (See Figures 6 and 7.) The helmet consisted of a plastic shell which had eighteen 2.5" holes. Slotted discs were fitted to the holes. Beckman electrodes were fitted into a tube against a synthetic sponge material. The synthetic sponge, Sugablök, was obtained from Sweden. The electrode tube was placed inside a second tube and held in place by a variable tension spring. This positioning tube was then placed in the slotted disc where it would protrude to the

scalp and cause the synthetic sponge to make contact with the scalp. The synthetic sponge was then impregnated a .15 molar Sodium Cholride solution to form a salt bridge for conductance of the evoked potential to the Beckman electrode. The overall advantages of the helmet are as follows:

a. The helmet provides firm placement of the electrode because of its rigid structure. The spring on the position tube maintains constant pressure of the electrode against the skin and provides more stable EEG measurements.

b. The helmet provides a great versatility. The slotted discs are rotatable and provide electrode placement at any position on the head. EEG measurements are thus reproducible because exact electrode placement is also reproducible.

c. The helmet provides easier and faster electrode placement. The electrode tubes are interchangeable in the helmet and may be snapped in or out in seconds. The synthetic sponge also eliminates the applying and re-applying of adhesive to re-position electrodes.

d. The helmet provides consistent EEG measurement. The synthetic sponge impregnated with NaCl solution provides a low resistance salt bridge between the electrodes and the skin. The compressibility of the sponge allows small sponge movement without resistive change or voltage measurement variance. In addition, moderate quantities of perspiration can be absorbed by the sponge without resistance variance.

Thus the helmet resolves the two major problems which cause varying electroencephalogram measurements.

11. Input CRT

An input oscilloscope was used to monitor the analog input signal to the processor to insure that an acceptable signal was being supplied to the signal processor.

12. Output CRT

An output oscilloscope, which is incorporated into the signal processor, was used to display the averaged EEG signal.

13. X-Y Plotter

The X-Y plotter reproduced the display of the output CRT. Thus the triggered audio signal and the audio evoked response were plotted for analysis.

14. Signal Processor

The signal processor was used to average the audio evoked cortical signal.

a. Operation

The continuous, filtered signal output from the electrodes was sampled at 256 times per second. According to the Nyquist sampling criterion, this sampling rate can effectively represent all signals that consist of frequencies of less than 128 Hertz. This frequency is more than adequate with the active filter removing all signals above 100 Hertz. The signal was sampled over consecutive 1 second intervals which were initiated simultaneously with audio spikes via the triggering by the pulse generator. As a result each sampling

interval and the audio evoked cortical response was synchronized with audio spikes. In addition, the pulse generator activated the audio spikes for only .5 seconds of each 1 second period. Thus every sampling period consisted of .5 seconds of stimulus followed by .5 seconds of rest. The synchronous EEG signals were averaged to obtain noise cancellation and to produce a relatively noise free audio evoked cortical response. A total of 128 one second periods were averaged to produce each of the final output audio evoked EEGs. The audio spikes were also passed through the signal processor to facilitate the plotting of the audio spikes along with its corresponding audio evoked cortical response.

The actual processor consisted of a Time/Data 1923 computer based Time Series System. The computer section of the signal processor consisted of a Digital Equipment Corporation PDP-11/40. All processing was done in real time so that data analysis was continuous throughout the testing procedure.

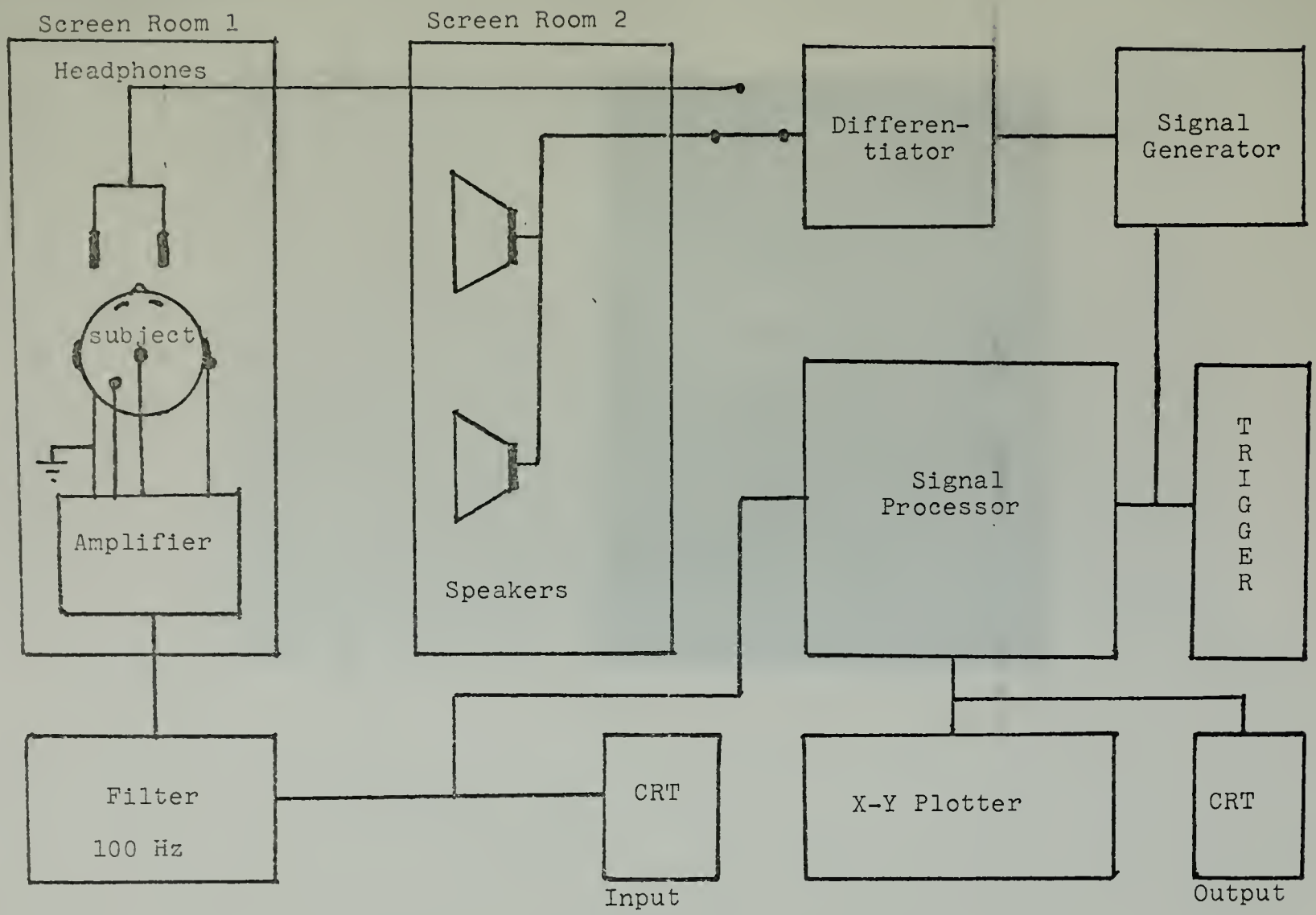


Figure 5. Laboratory Testing Diagram.

Tension Nut Position Tube Electrode Tube

Figure 6. EEG Helmet Components.

Figure 7. EEG Helmet.

VI. RESULTS AND ANALYSIS

A. TIME AVERAGING

The signal averaging performed by the Time/Data Time Series system was conducted over 128 one second intervals. The analog signal was digitally converted into 256 parts over the one second interval. After one second period the values of the signal in the corresponding digital points were summed. At the end of the summation process the value of each of the 256 digital parts of the signal were divided by 128 to produce a normalized waveform with the original scale corresponding to the signal in a single one second interval.

The concept behind signal averaging is to reduce the noise level. In the case of EEG analysis, the concept is further extended to the reduction of signals which are not uniformly present in each data frame. As previously stated, the EEG is a composite signal which represents many processing functions occurring simultaneously within the brain. If a stimulus and time averaging processor are synchronized, simultaneous processing that is not uniform with each averaging frame and hence not directly resulting from the stimulus is reduced through the average. The resulting waveform from the averaging is a representation of the evoked response because the random processing signals are reduced while the constantly occurring evoked response is additive and therefore dominant.

The amount of random signal reduction is a function of the number of frames that are averaged. Theoretically, the variance of N number of independent random signals is equal to N times the variance of a single signal. Or stated in mathematical terms:

$$\sigma_N^2 = N \cdot \sigma^2 .$$

The root mean square value of the signal is the same as the square root of the variance. Thus the RMS value of N random signals is equal to the square root of the variance of N signals or;

$$RMS_N = \sqrt{N \cdot \sigma^2} = \sqrt{N} \cdot \sigma .$$

If the peak amplitude of a non-random signal is called $\hat{V}$, then the combination of N of these signals is equal to $N\hat{V}$. The ratio of the non-random signal peak amplitude to the RMS random signal level can be expressed as the signal-to-noise ratio which is:

$$\frac{N \cdot \hat{V}}{\sigma \cdot \sqrt{N}} = \sqrt{N} \cdot \frac{\hat{V}}{\sigma} \equiv \text{Signal-to-Noise Ratio.}$$

Thus it can be seen that the signal-to-noise ratio improves with the square root of N.

Thus the signal averaging with 128 sampling interval reduces the noise by a factor of the square root of 128 or by about 11 times. Or speaking from a different point of view, the audio evoked EEG signal is enhanced by an amplification factor of 11.

B. ARTIFACTS

A major problem in delivering stimuli to a subject for EEG testing is the contamination of the EEG signal by the stimulating source. This was found to be a significant problem in the early testing for this research project. The earphones and speakers both produced artifacts in the EEG signals. Attempts to remove these artifacts by aluminum foil shielding about the earphones produced only minor reduction in the contaminating signal. Because the shielding failed, the interference was deemed to be a magnetic field interference rather than an electric field. Both electrostatic and dynamic headphones were tried but neither produced satisfactory results.

The resolution of such a problem is quite important and often overlooked in EEG analysis. The result, of course, is the analyzing of a combined EEG and outside source signal which produces invalid results. What some have considered as cortical responses are often signals which play no role to brain processing at all.

The best solution to the artifact problem was the placement of two audio speakers in a separate screen isolation room adjacent to the screen isolation room in which the subject was tested. Both screen isolation rooms were grounded and provide adequate shielding and distance between the artifact source and the EEG electrodes placed on the subjects head. Verification that the residula artifacts that might be passing between the two screen rooms was insignificantly

small was accomplished through long term signal averaging with no artifact appearing in the averaged waveform.

C. AVERAGED SIGNAL RESULTS AND ANALYSIS

Upon completion of the audio testing, the averaged evoked cortical potentials were analyzed. It was not difficult to see that there was a definate response. Comparison of EEG waveforms from different subjects in response to the same stimuli showed almost exact duplication of the evoked potentials. The minor differences that did occur were in timing between the dominant peaks which, in any case, did not exceed 50 milliseconds. Such a small timing difference is a good verification that audio processing in most individuals occurs at the same rate and in a similar manner. Some previous study has identified cortical responses to pulsed sinsoidal tones. But previous identification did not show the detail which resulted in the research conducted for this research project. This was probably due to the fact that a greater number of averaging frames were used in this research and a better evoked signal enhancement occurred. The equipment used for this project represents the state-of-the-art in EEG processing. It is not odd then that portions of the EEG not previously observed are now apparent with such processing.

The unit response to a single audio click consisted of a waveform with nine recognizable peaks. Figures 8 through 12 depict the audio evoked response with the peaks numbered

1 through 9 and the audio pulse labeled as P. The first positive peak occurred at 35 milliseconds after the stimulus. The variations in timing of this peak was 10 milliseconds in either direction. The first negative peak was not always apparent but occurred at 55 milliseconds with the same variation as the first positive peak. The second positive peak occurred at 75 milliseconds and the second negative peak occurred at 100 milliseconds with both peaks having 15 millisecond variations. The third positive peak was the most prominent of all of the peaks observed and occurred at 140 milliseconds with a 15 second variance in a few instances. Peaks six and seven, which were negative and positive respectively, were the least observable of the peaks. Peak six occurred in the 190-230 millisecond interval while peak seven occurred in the 210-250 millisecond interval. The interval between peaks six and seven was 20 milliseconds. The final negative peak had the widest variance in time of occurrence. In most cases the peak occurred at 300 milliseconds with a variance of 50 milliseconds in several cases. The final positive and terminating peak of the audio evoked unit response was consistent in its appearance at 380 milliseconds after the stimulus and varied only by 10 milliseconds in either direction.

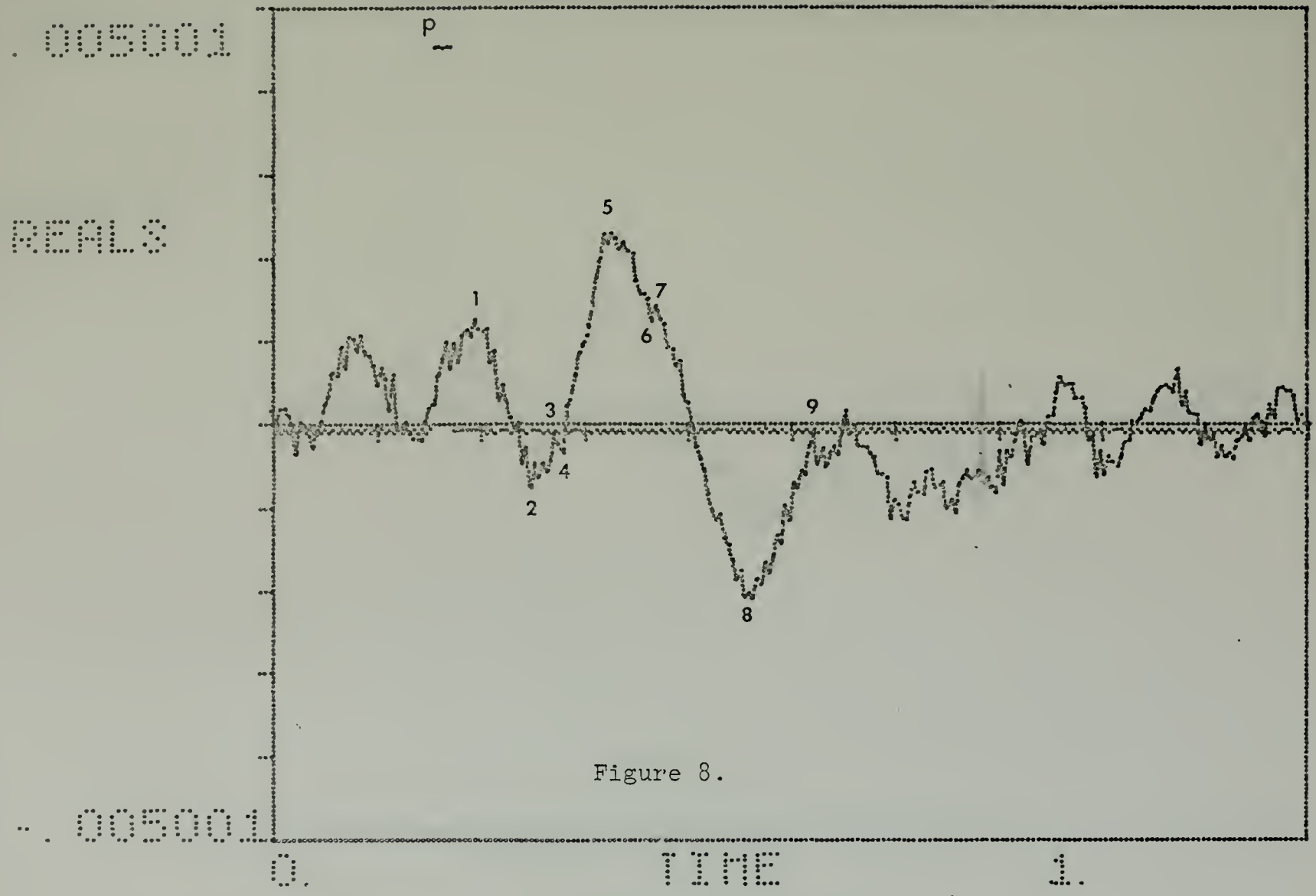
An important point that was examined was the effect of the amplitude of the audio stimulus. Testing showed that amplitude variations over moderate intensity levels produced a relatively consistent waveform with the dominant features

of the audio evoked unit response. Figures 8 and 9 were made using an audio signal which varied 10 db with Figure 9 having the higher volume level. As can be observed, no noticeable differences are seen. Thus the response waveform is not a function of amplitude intensity.

Following identification of the unit response, the audio evoked response to two or three clicks was observed. These results are shown in Figures 14 through 18. The peaks corresponding to the individual audio pulse marked as P are labeled as 1-9 for the first response peaks, 1'-9' for the second response peaks, and 1*-9* for the third response peaks. As expected, the individual peaks for each of the unit responses were still observable. The processing of one unit response overlaps the other and an integrative type processing occurs. The composite waveform can be predicted by overlapping the unit responses at the proper intervals. A similar result was observed in visual evoked responses that were examined in previous research by the Bio-Engineering team at the Naval Postgraduate School and it did not seem odd that the audio evoked response produced a similar waveform.

Finally, verification that the averaging program used was functioning correctly was accomplished by averaging the EEG response obtained with no audio source supplied to the subject. As expected, the EEG waveform was random and tended to average to zero. Figures 19 through 22 show the results to a no stimulus averaging of three different subjects.

It was noted that cortical processing of audio signals occurs during sleep. The 11 year old fell asleep during the testing and produced the averaged response found in Figure 13. The only significant difference in the waveform during sleep is an increased latency of peak timing after the stimulus. The basic waveform remained the same. This could indicate a similar but slower audio cortical processing during sleep. The method in which one teaches himself to wake to certain sounds and not others is valid proof of the continuous audio processing during sleep.



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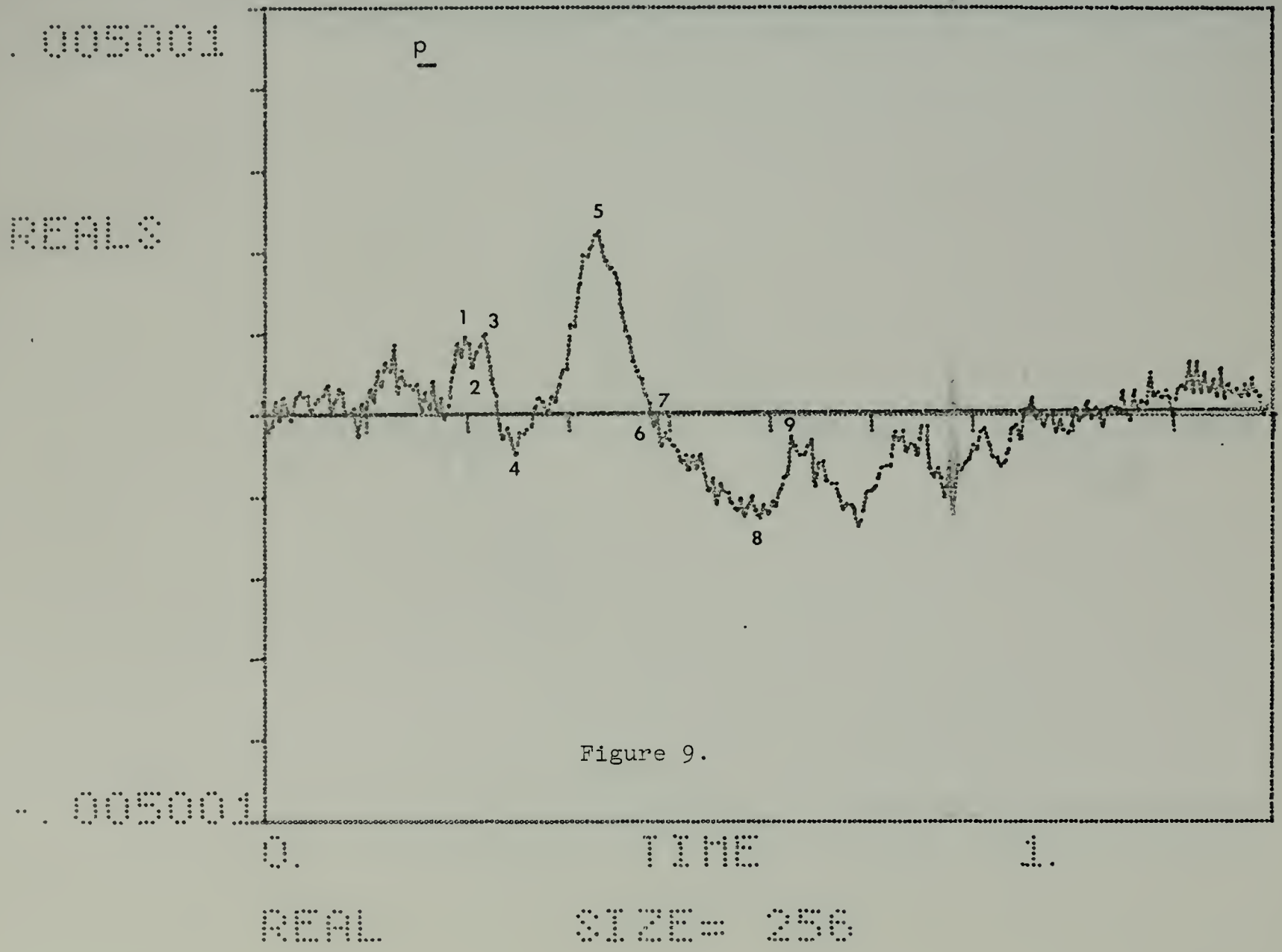

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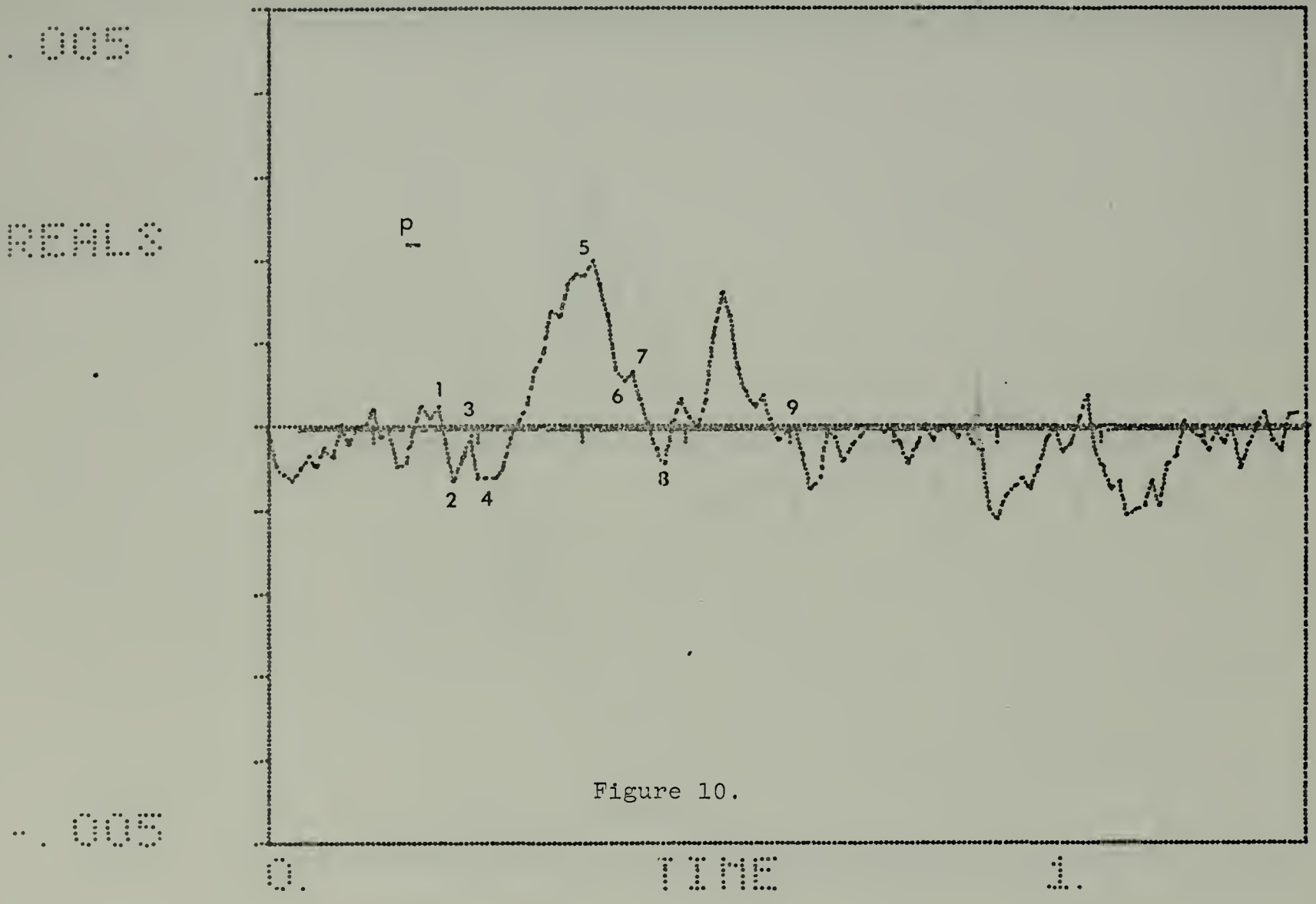

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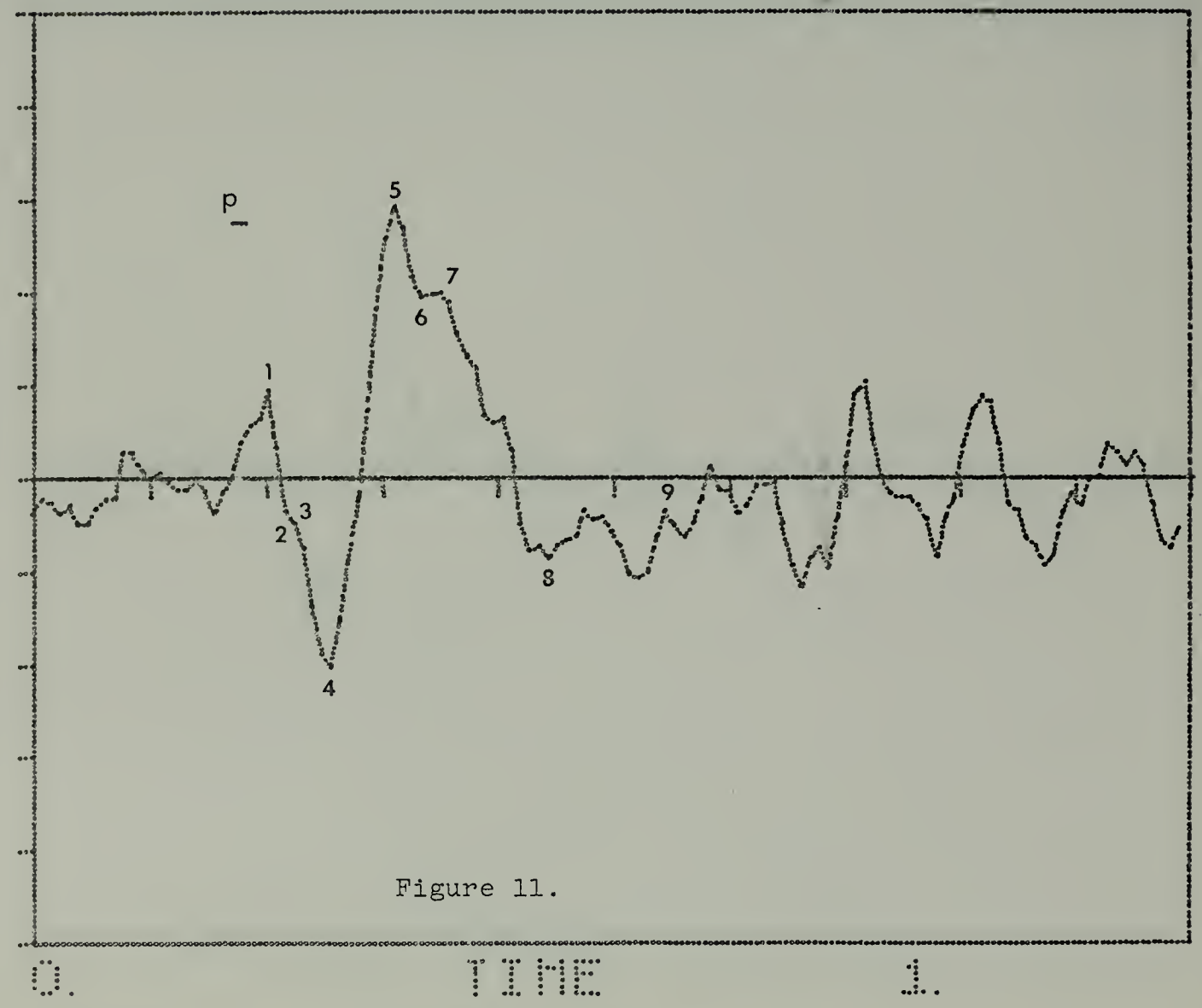

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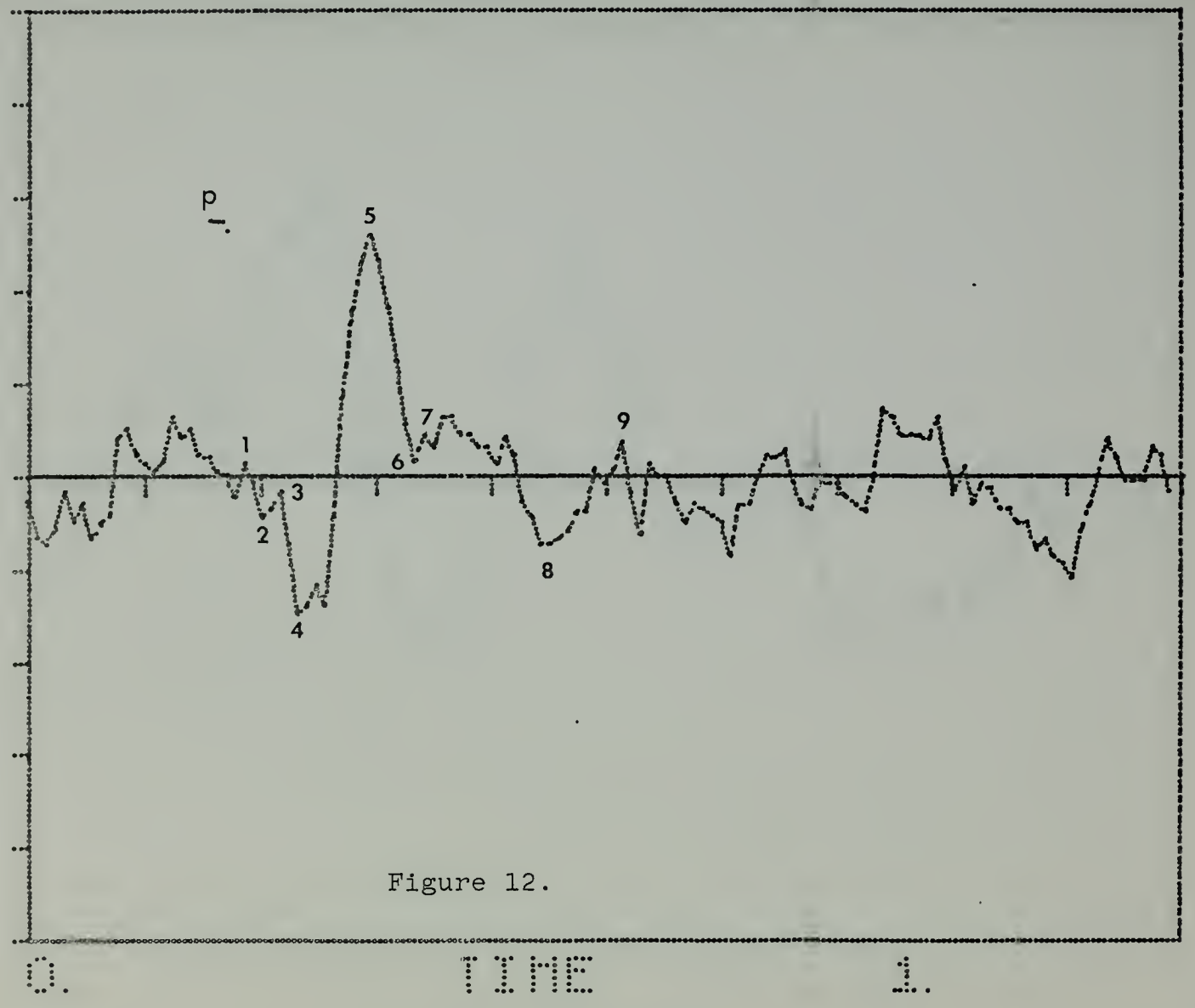

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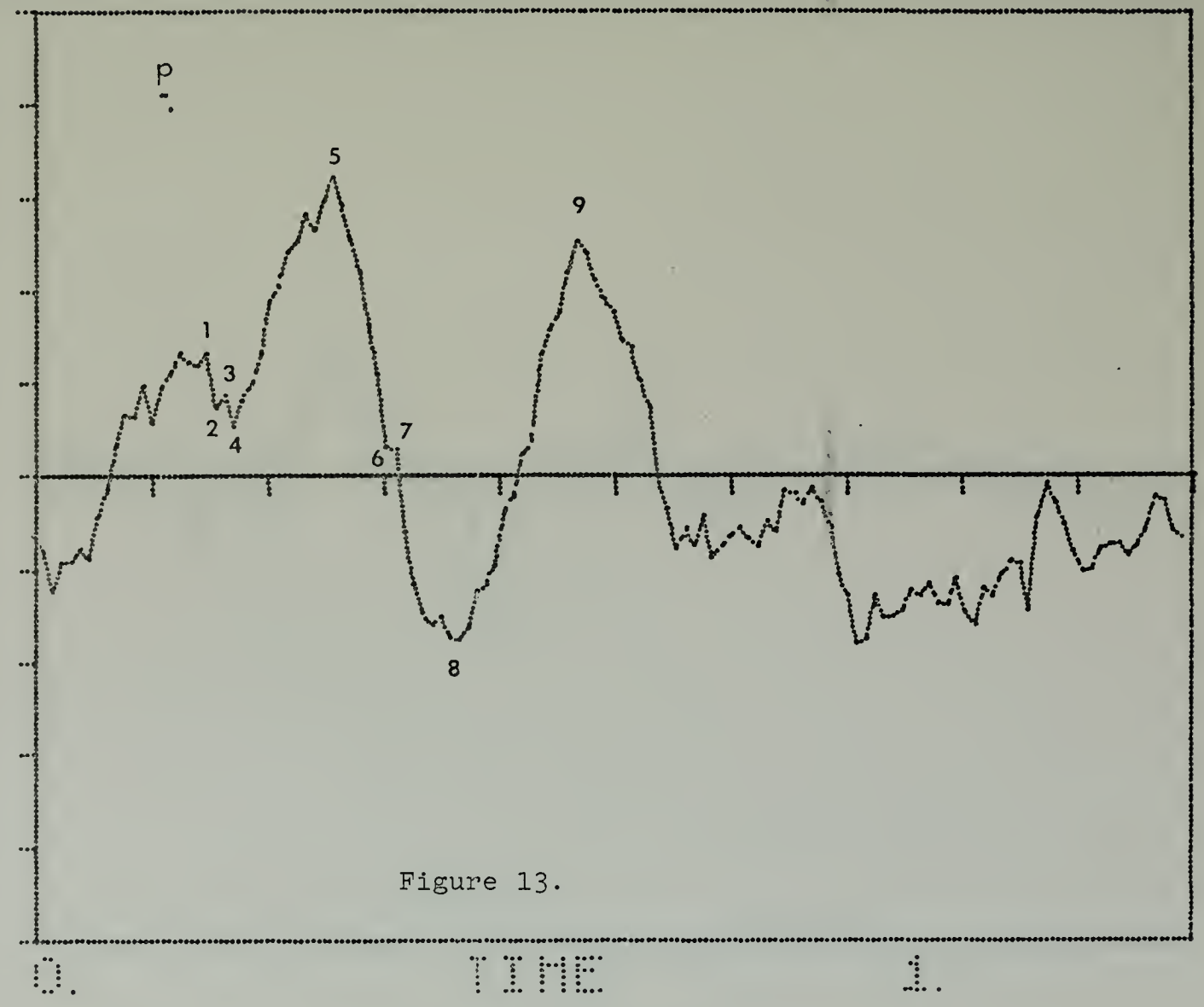

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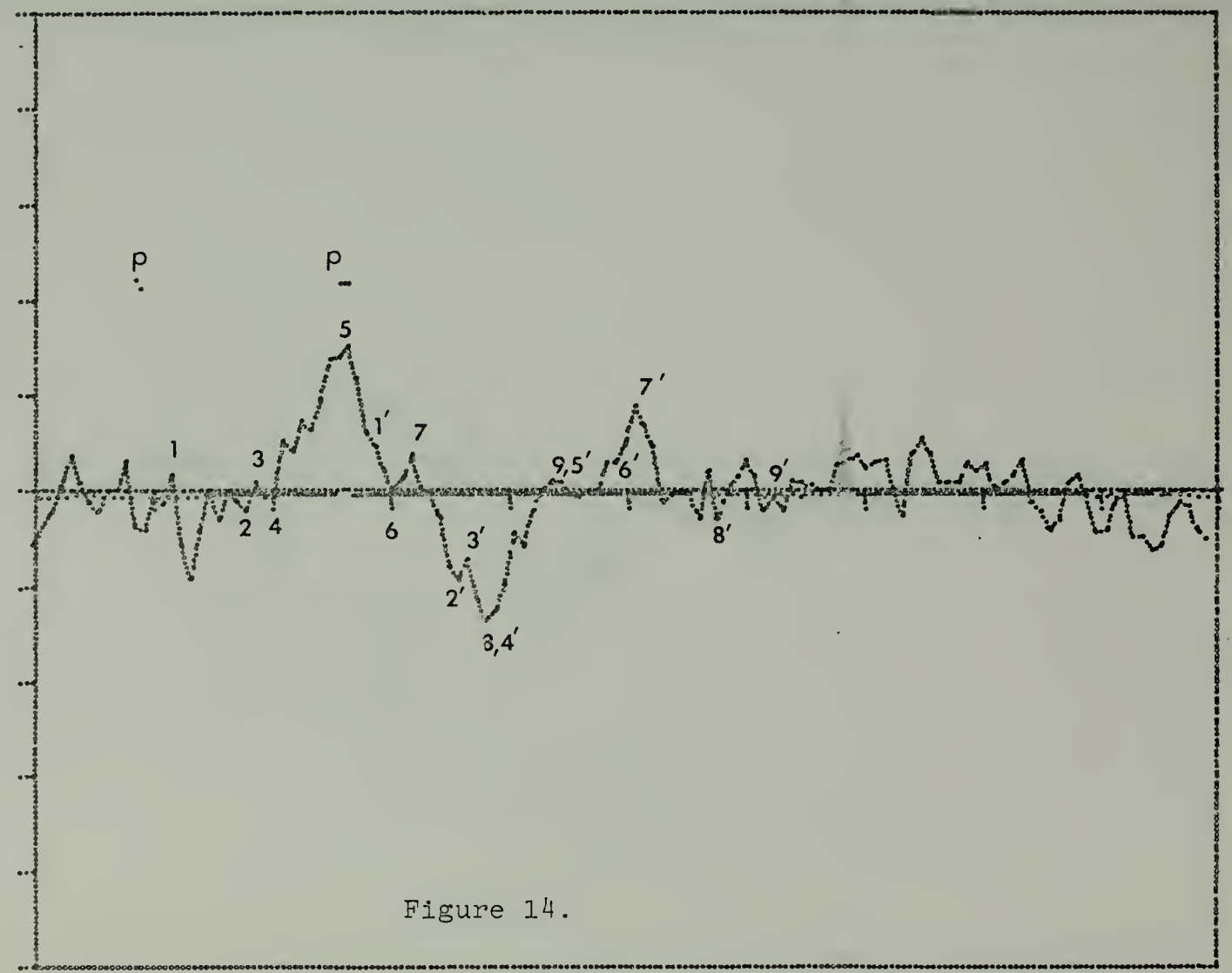

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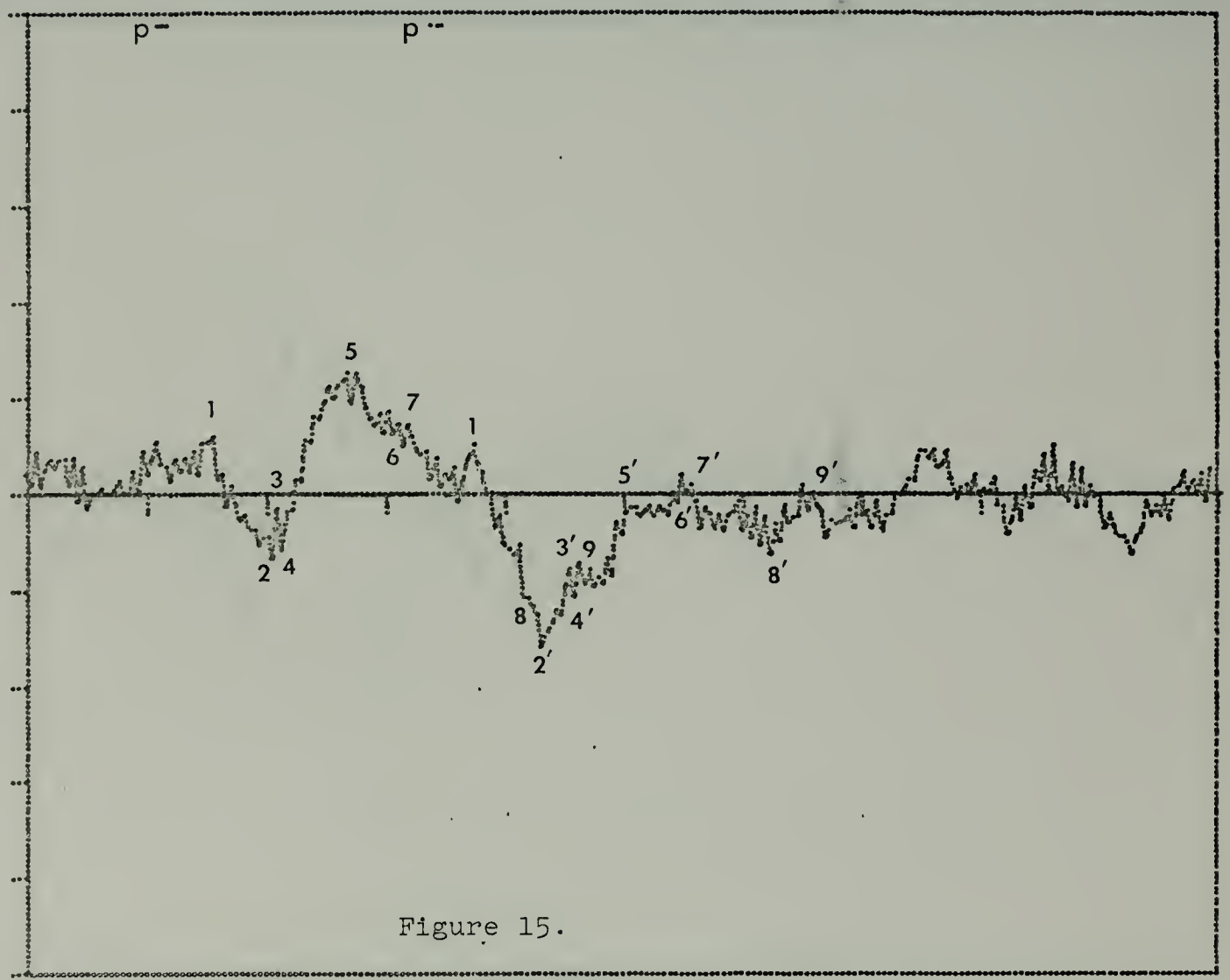


Figure 15.

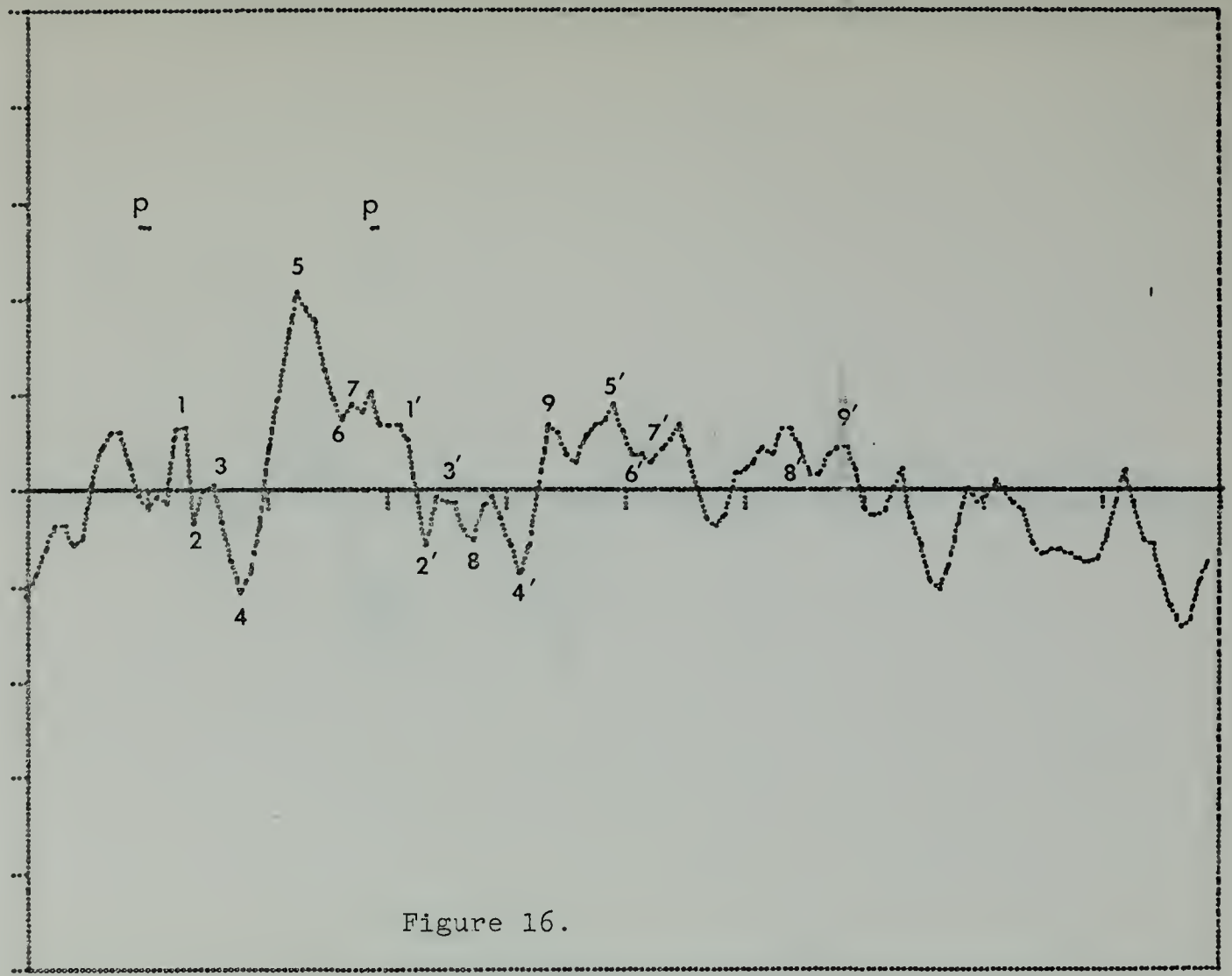
. 005

REALS

. . 005

0. TIME 1.

REAL SIZE= 256



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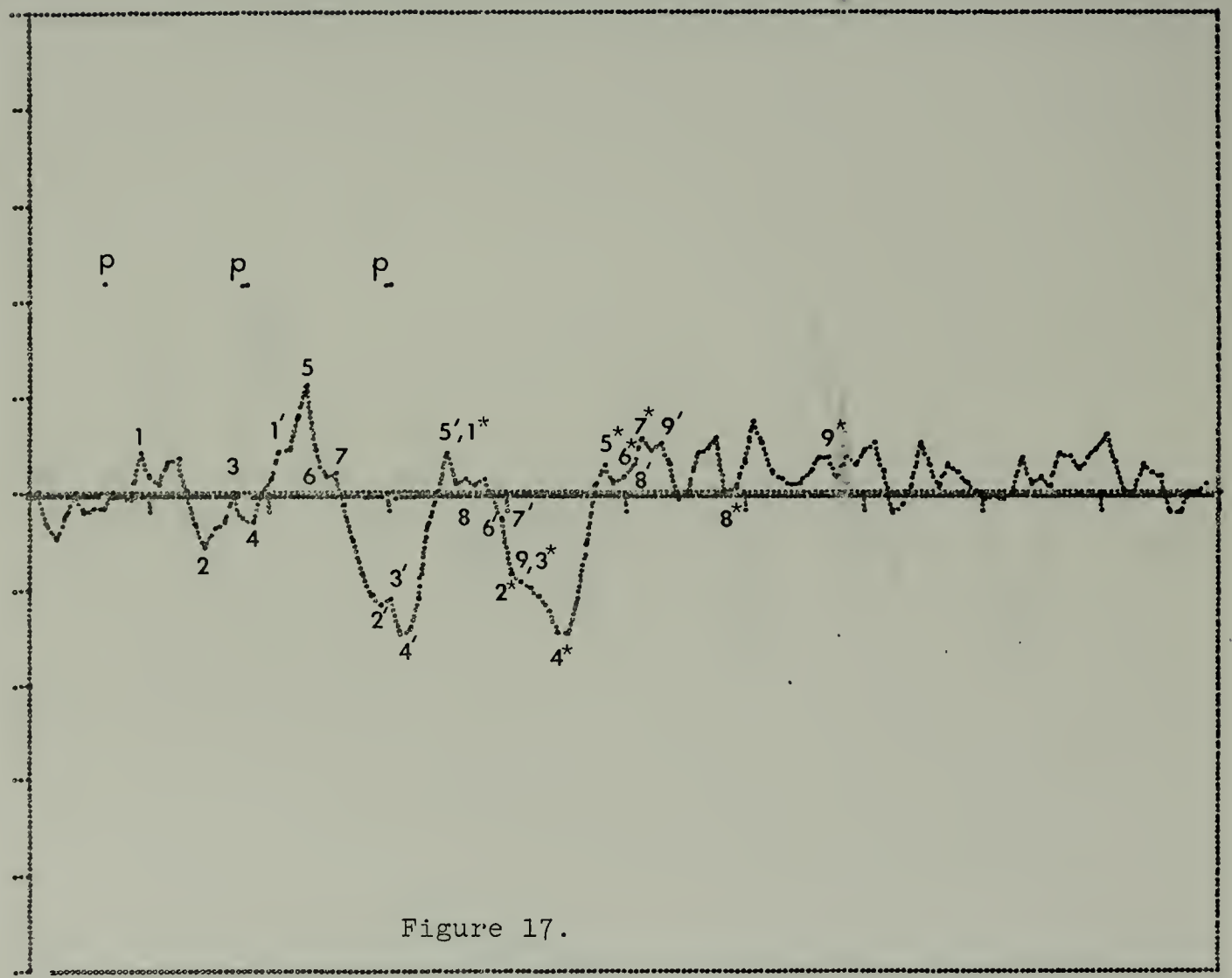


Figure 17.

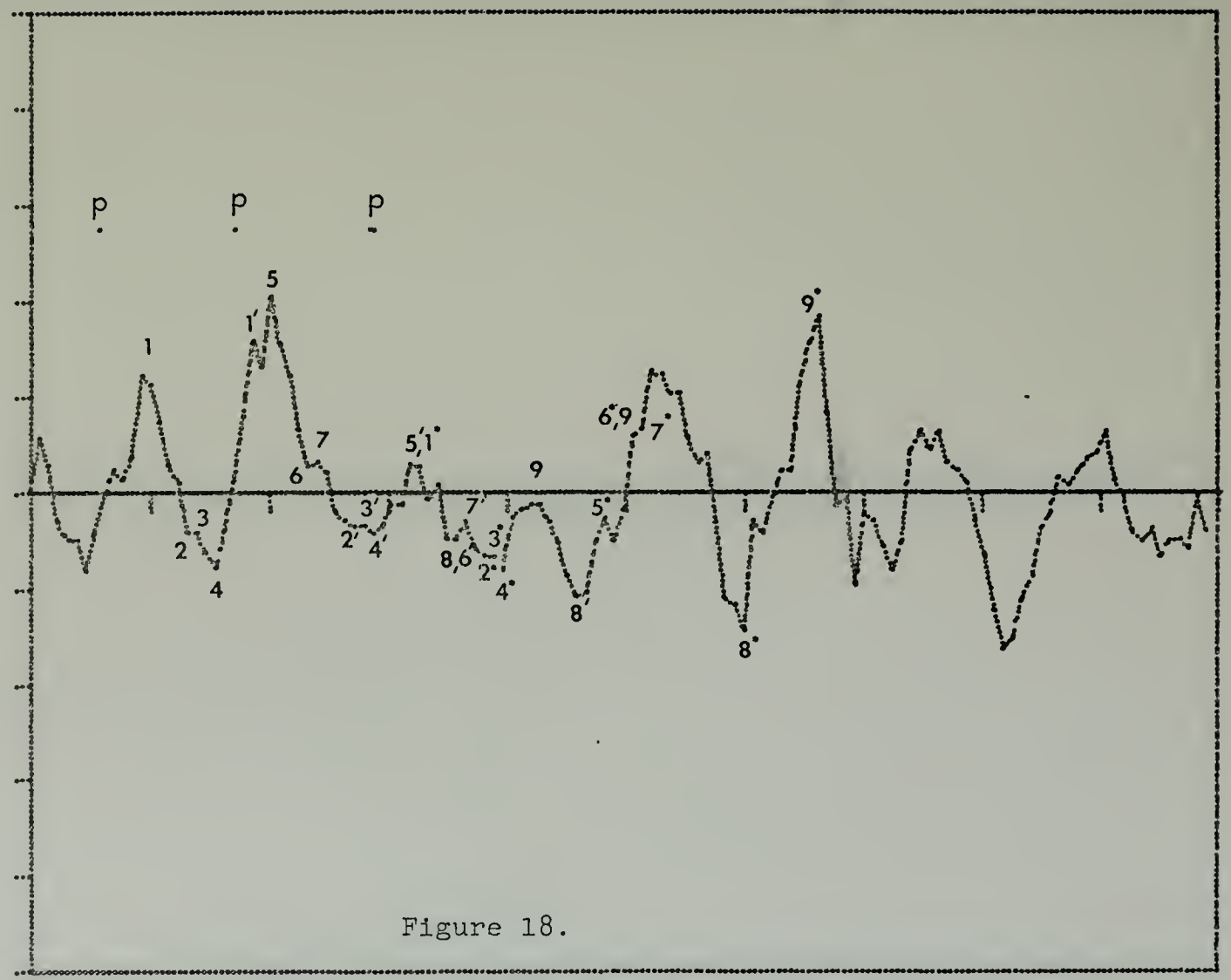


Figure 18.

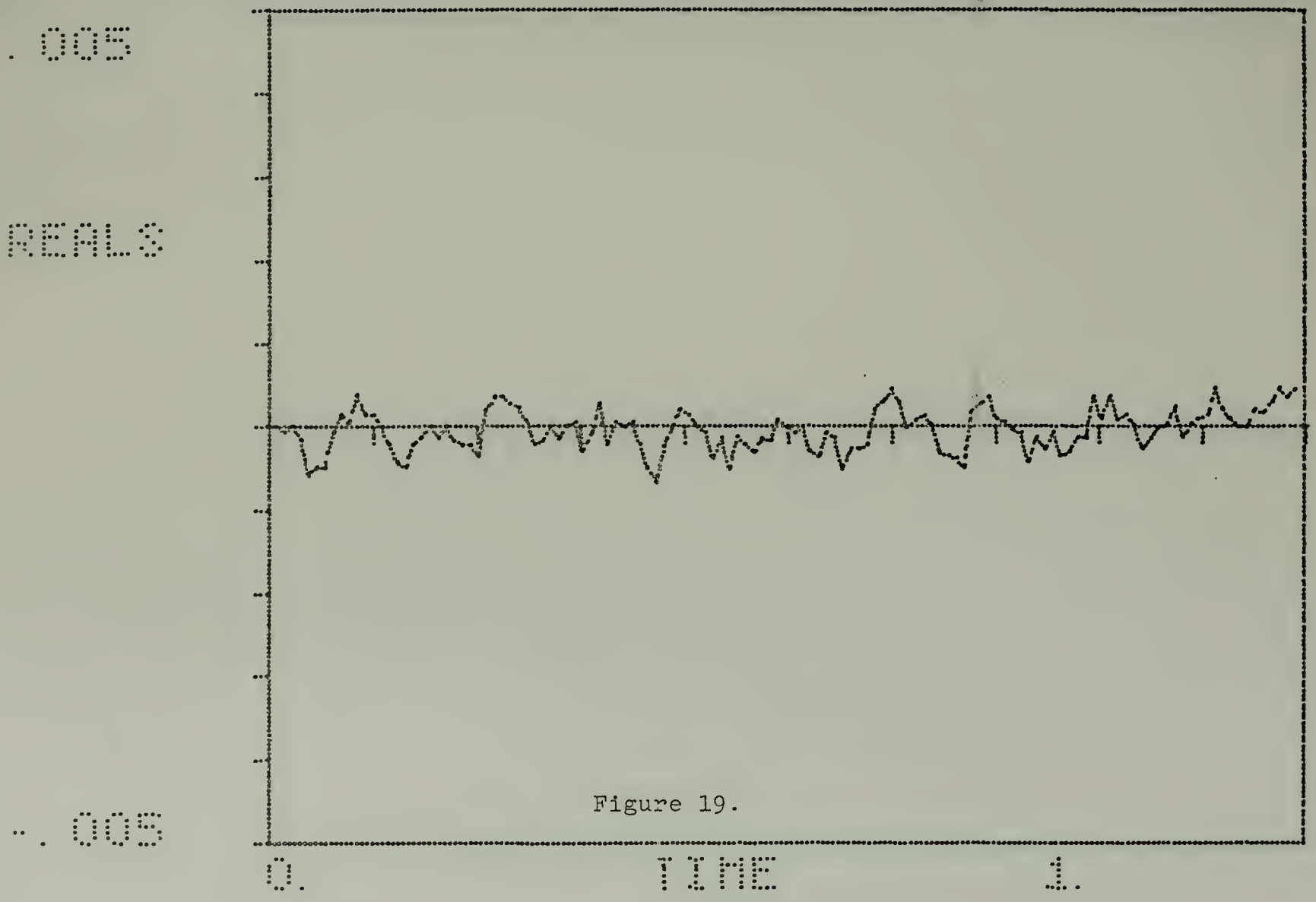
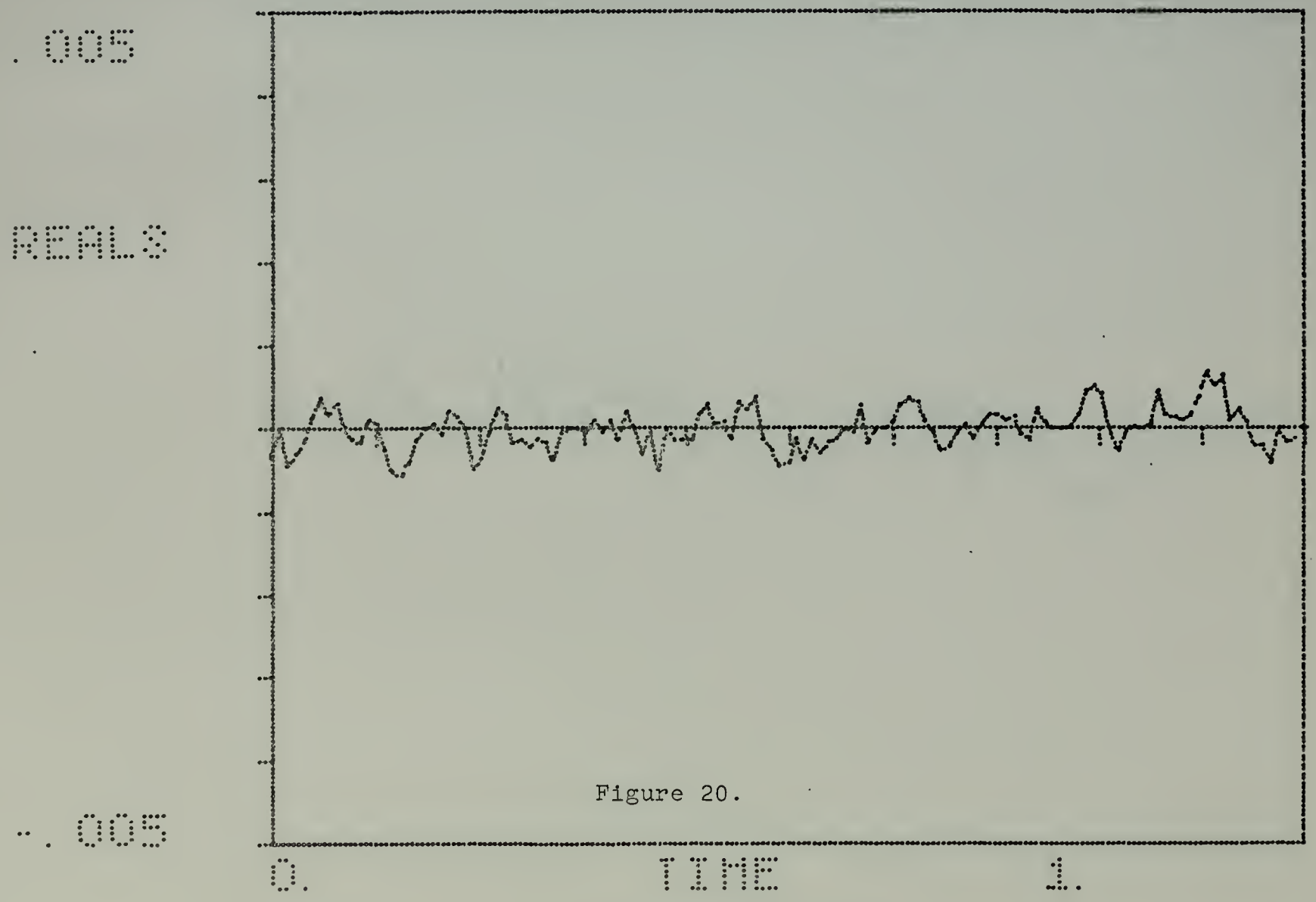


Figure 19.



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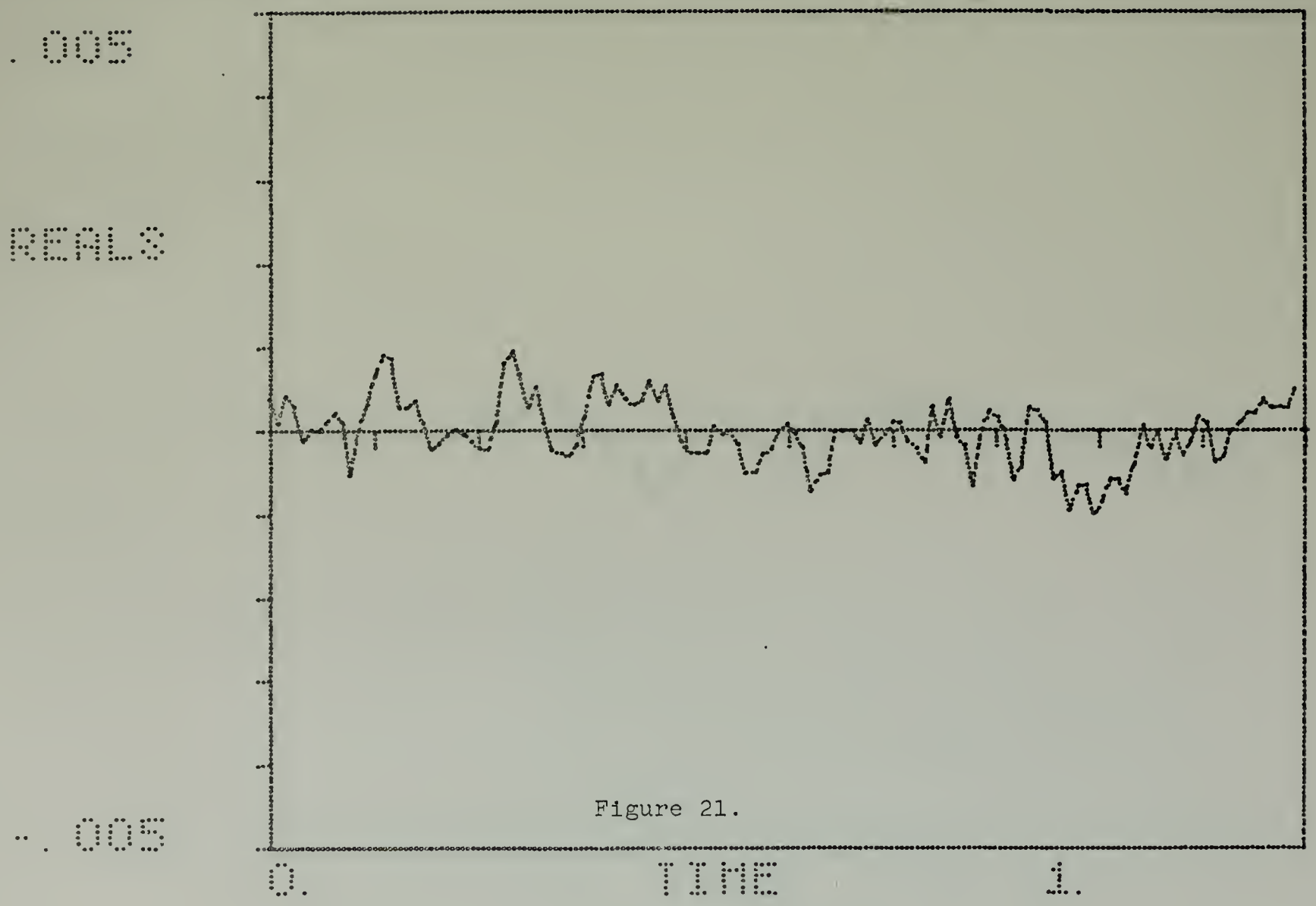

Figure 21.

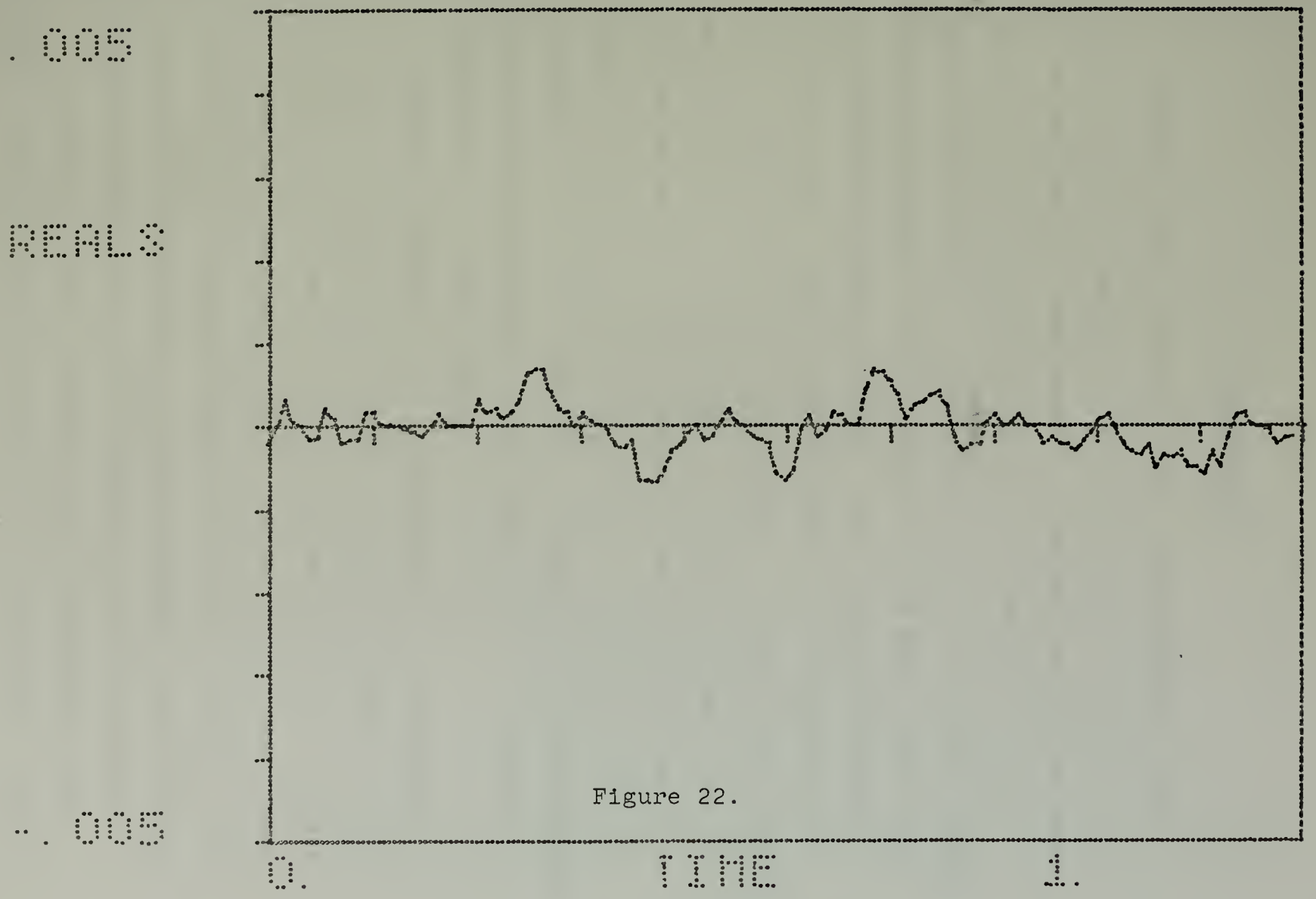

Figure 22.

VII. DISCUSSION

Specific identification of the characteristic audio evoked cortical response will allow for the accurate analysis of audiometric test results. Through the EEG the testing will be an objective testing. The benefit of such objectivity is great. Audiometric test will be more accurate because the subject will not have to take part in the testing procedure except to listen. Even unwilling subjects, such as infants, cannot help but hear the presented stimulus. Thus audio testing can become a routine and accurate test for infants. Extensions of the EEG audiometry can be used to remove the costly problem of malingerers that is presently troubling the Armed Forces. Testing requires no specific skill for the subject. It does not require knowing any particular language or skill and is thus a uniform testing procedure for all people.

Through analysis of the waveform and its correlation to the audio pathway to the brain, it may be possible to determine the exact location of neurological problems. Absence of a dominant peak may identify lack of a junction or nonfunctioning of a junction along the auditory pathway. Obviously, the localization of a neurological problem along the audio pathway may help in the cure of that problem.

Through the identification of the processing of the audio centers of the brain and their identification through

electroencephalograms, a better understanding of brain functioning in the audio area may be achieved. The understanding of the audio processing will be a step towards the understanding of speech processing, visual processing, and the total processing which occurs within the brain.

Finally, it is interesting to note that the general form of the audio evoked cortical response seems to resemble the alpha wave. It has been suggested that the alpha wave acts as a type of clocking or strobing signal for brain processing. It could thus be hypothesized that the cortical processing reaction to a stimulus results in the resetting of the alpha wave in a local area of the brain. In both audio evoked cortical responses and visual evoked cortical responses, an unit response of the alpha shape was produced. A local resetting of alpha circuits within the brain could be a plausible theory which is enforced by the results of this as well as previous EEG analysis.

VIII. SUMMARY

The audio evoked cortical response has been identified and confirmed. In fact, the unit response to a single stimulus has been identified as a waveform consisting of nine major peaks. These peaks are constantly present and can be identified through their consistent time of occurrence after the stimulus.

The audio evoked response has also shown to integrative. That is, the waveform resulting from the processing of multiple audio stimuli is composed of the individual unit responses to a single stimulus which are integrated, but still distinctive, into a composite waveform.

Variations of the amplitude of the stimuli within a moderate range shows that the unit response maintains its characteristic form. The waveform does not occur until a threshold level is attained and remains of constant form until extreme volume levels occur.

The differences in waveform of the audio evoked cortical response is not characteristic of males, females, children of either sex, or age.

All results obtained verified that the audio evoked cortical response is a characteristic response which is nearly identical in all subjects tested.

It was also verified that a greater latency in the audio evoked cortical unit response occurred when the subject was

asleep. All dominant features of the unit response were present, but the times of occurrence after the stimulus was greater. Thus it can be concluded that ∠udio processing does occur during sleep, but in a different manner in relation to processing time.

An electrode helmet was designed and produced which facilitated the measurement of EEG response with greater ease. The helmet allows duplication of electrode placement while removing the present problems of varying resistance and varying voltages from the electrode measurements. Thus the means for making rapid, reliable, and repeatable EEG measurements is available.

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